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# Poly(*meta*-phenylene oxides) for the design of a tunable, efficient, and reusable catalytic platform

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We present poly(*meta*-phenylene oxides) as versatile and tunable scaffolds for immobilized catalyst design. Their modular synthesis enables the rational incorporation of different side chain groups with positional control along the polymer backbone, providing an easy means to modulate polymer properties, and their corresponding catalytic activity. The coordinative convolution of these polymers with  $(NH_4)_2PdCl_4$  affords efficient, reusable catalysts for various transformations.

In the world of catalysis, researchers are often torn between homogenous and heterogeneous systems.<sup>1</sup> Homogeneous catalysts often offer superior activity because of their equal distribution within the reaction media, and the availability of highly tunable ligand architectures.<sup>2</sup> Heterogeneous catalysts, on the other hand, typically suffer from decreased catalytic activity but enable easier recovery and recycling.<sup>3</sup>

Our pursuit of solid-supported nanocatalysts<sup>4</sup> fuels investigations into the coordinative convolution of polymers bearing imidazole,<sup>5</sup> pyridine<sup>6</sup> and similar N-heterocycles with Pd,<sup>5a,6b</sup> Cu,<sup>5b,6a</sup> and other metals. Despite its role as an excellent Pd ligand,<sup>7</sup> pyrimidine-bearing polymers<sup>8</sup> have yet to be explored in this context.<sup>5,6,9</sup>

The synthesis of poly(*meta*-phenylene oxides)  $(poly(mPOs))^{10}$  provides a convenient route to such pyrimidine-bearing amphiphilic polymers as main-chain polymer ligands, as well as those containing bidentate 1,10-phenanthroline ligands. Unlike many of the more conventional polymers thus far used for catalyst immobilization via coordinative convolution,<sup>5,6,9</sup> these poly(*m*POs) offer straightforward and structured tuning by the incorporation and variation of side chain groups, while leaving the fundamental backbone unchanged. These



**Scheme 1**. Tunable Synthesis of poly(*m*POs)

poly(*m*POs) thus attracted our attention for their unexplored metal-binding ligands, as well as for their tunability.

Reaction of dihalide electrophilic (A) and diphenol nucleophilic (B) coupling partners affords these thermooxidatively robust ABAB-type poly(*m*POs).<sup>10a</sup> Typically, the diphenol and electrophile (pyrimidine,<sup>11</sup> pyrazine,<sup>11a</sup> pyridine,<sup>12</sup> triazine,<sup>13</sup> or nitro-,<sup>14</sup> nitrile, or acetylene-<sup>15</sup> substituted benzene) coupling partners will react to form small cyclic oligomers (oxacalixarenes).<sup>16</sup> However, with specific electrophiles, poly(mPOs) can be generated under kinetic conditions.<sup>10a</sup> Prior studies demonstrated the kinetic polymerization using two electrophilic scaffolds, 4,6-dichloropyrimidines, and 2,6dihalobenzonitriles. Herein we expand the scope of poly(mPOs) derived from 4,6-dichloropyrimidines (A1), and introduce 4,7-dichloro-1,10-phenanthroline (A2) as multicyclic aromatic electrophile that has not previously been used in either poly(mPO) or oxacalixarene syntheses. In this work, we leverage the tunability and functional group tolerance of this novel synthesis (scheme 1) toward industrially relevant, recyclable catalysis for aqueous Suzuki, Heck, and hydrogenation reactions effective in the PPM-PPB metal loading range.

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Styrene hydrogenation catalyzed by (NH<sub>4</sub>)<sub>2</sub>PdCl<sub>4</sub>@poly(mPO)**1a-c** was evaluated in order to probe the relative effect of pendant side chain groups not directly involved in metal binding (Figure 2). By increasing the hydrophobicity ( $R^1 = H < CH_3 < C_5H_{11}$ ), the yield for styrene hydrogenation after 12 hours decreased in cyclohexane (94  $\rightarrow$ 42%), but steadily increased in water (52%  $\rightarrow$  95%). The increased reactivity in water likely stems from the more hydrophobic polymer's ability to better attract the nonpolar styrene into the polymer matrix to interact with the active

B (NH<sub>4</sub>)PdCl<sub>4</sub>@Poly(mPO) 1a-c Solvent (1 mL), 40°C, 12 hr 0.5 mmo H<sub>2</sub> (balloon) CH3 C5H11 R<sup>1</sup> н 100 80 Yield (%) 60 Solvent: Water 40 Cyclohexane 5 7 9 11 13 15 17 Log P estimates (polymer hydrophobicity -

Figure 2. Tuning Poly(mPO) Hydrophobicity for Improved Aqueous Hydrogenation

palladium species.

We further explored Suzuki coupling under aerobic and aqueous conditions, which tend to be problematic for Pd/phosphine systems. In exploring our full range of as prepared Pd@poly(mPOs), we found no advantage to hydrophobicity tuning or the use of more complicated bidentate phenanthroline or bipyrimidyl systems. Thus, we proceeded with the simplest polymer (poly(mPO) **1a**) derived from the most abundant, widely available monomers. As shown in Table 1, Pd@poly(mPO)1a efficiently catalyzed Suzuki reactions of aryl boronic acids with aryl chlorides bearing neutral substituents (Entries 1-2), electron withdrawing groups (Entry 3), and strong electron donating groups (Entries 4-6). Coupling of the less reactive trans-2phenylvinyl boronic acid proceeded smoothly with either bromo- or iodobenzene, but negligible product was observed for chlorobenzene (Entry 7). To investigate catalyst TON (Entry 8), coupling of 4-iodotoluene with phenylboronic acid was carried out at Pd loadings of 400 mol PPM (99 %), 40 mol PPM (97%), 4 mol PPM (99%), and 400 mol PPB (75%, TON = 1.9 million). Reusability of the catalyst was demonstrated by measuring the initial reaction rates for recycling runs (Entry 9). Through 5 cycles of catalysis, the initial reaction rates did not significantly decrease. In further support of a heterogeneous mechanism, we found that (NH<sub>4</sub>)<sub>2</sub>PdCl<sub>4</sub> was incapable of catalyzing the coupling of aryl chlorides to phenylboronic acid, even with the addition of the closest available homogeneous



HRTEM of nanoparticle lattice spacing (B). TEM images (C) and XPS (D) of nanoparticles as-synthesized (before) and

Poly(mPOs) were readily prepared by the reaction of a 1,3diphenol with an equimolar amount of dihalogenated

electrophile and excess K<sub>2</sub>CO<sub>3</sub> in DMSO at 100-150°C (SI).

Without directly affecting the site of metal binding, the hydrophobicity of the polymer systems could be modified by

varying the nature of R<sup>1</sup> (H, methyl, *n*-pentyl) on the diphenol

unit. The coordination environment of the pyrimidine units (A1) could likewise be modulated by varying  $R^2$  from among H, Ph, N-morpholino, or even by the incorporation of a second

pyrimidyl unit, enabling incorporation of a 2,2-bipyrimidine

scaffold integrated into the polymer backbone. Alternatively,

the bidentate 1,10-phenanthroline unit could be directly

incorporated by use of the electrophile 4,7-dichloro-1,10-

Coordinative convolution of each polymer was achieved by

mixing a solution of (NH<sub>4</sub>)<sub>2</sub>PdCl<sub>4</sub> (0.15 mmol in 2 mL H<sub>2</sub>O) into a

solution of poly(mPO) (1 mmol in 2 mL CHCl<sub>3</sub>). After stirring

vigorously for 3 hours at 60°C, the mixture was diluted with

acetone, and the globular, insoluble Pd-polymer complex was

washed with H<sub>2</sub>O, acetone, and chloroform. XPS analysis of the

resultant (NH<sub>4</sub>)<sub>2</sub>PdCl<sub>4</sub>@poly(mPOs) indicated Pd present as

mostly PdCl<sub>2</sub> with some PdO (Figure 1a). TEM analysis

identified PdO nanoparticles (3.2 +/- 0.6 nm) distributed

evenly throughout the polymer matrix (Figure 1b). SEM/EDX

elemental mapping likewise demonstrated an even

distribution of both Pd and Cl (Figure 1c-d). Loading of each

Pd@poly(mPO) complex was carried out via ICP-MAS, ranging

from 0.32-0.89 mmol/gram. The coordination of Pd to multiple

pyrimidine or phenanthroline ligands serves the dual role of

cross-linking the polymer and stabilizing the reactive metal

after use in Suzuki coupling (after).

phenanthroline (A2).

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analogue (4,6-dimethoxypyrimidine) to the polymeric complex, indicating the cooperative affect of the Pd/polymer complex (Entry 10). Furthermore, ICP analysis after catalysis likewise measured very little (0.17 PPB) Pd leached from the polymer matrix during the course of a typical Suzuki coupling reaction (Entry 1). Pd@poly(mPO)1a outperformed the commercial heterogeneous catalyst with our TON ranging from two<sup>19</sup> to five<sup>18</sup> orders of magnitude greater than Pd/C1<sup>7-19</sup> (Table 2). Our system likewise outperformed Pd(PPh<sub>3</sub>)<sub>4</sub><sup>20</sup> and Pd<sub>2</sub>(dba)<sub>3</sub>,<sup>21</sup> although our TON and TOF fell short of a homogenous (non-recyclable) system catalyzed by trace impurities of Pd found in other reagents.<sup>22</sup>

Table 1. Aqueous Suzuki Coupling

Ar-X + R-B(OH) <sub>2</sub> $\xrightarrow{Pd@Poly(mPO)}$ Ar-R TBAB (optional), K <sub>3</sub> PO <sub>4</sub> , H <sub>2</sub> O, 95°C			
Entry	Ar	R	Yield
1	4-Me-C <sub>6</sub> H <sub>4</sub>	Ph	Cl: 97 (isolated)
2	Ph	4-Me-C <sub>6</sub> H <sub>4</sub>	Cl: 98 (GC)
3	4-CN-C <sub>6</sub> H <sub>4</sub>	Ph	CI: 97 (isolated)
4	4-NH <sub>2</sub> -C <sub>6</sub> H <sub>4</sub>	Ph	CI: 94 (isolated)
5	4-OH-C <sub>6</sub> H <sub>4</sub>	Ph	CI: 95 (isolated)
6	4-OMe-C <sub>6</sub> H <sub>4</sub>	Ph	CI: 94 (isolated)
7	Ph	C ~ ~	l: <sup>a</sup> 98 (isolated) Br: 95 (GC) Cl: 1 (GC)
8	4-Me-C <sub>6</sub> H <sub>4</sub>	Ph	l: 99, <sup>b</sup> 97, <sup>c</sup> 99, <sup>d</sup> 75, <sup>e</sup> (GC)
9	$4-\text{Me-C}_6\text{H}_4$	Ph	CI (initial rates, $\mu$ mol/min): 1.4, <sup>f</sup> 1.3, <sup>g</sup> 1.5, <sup>h</sup> 1.4, <sup>i</sup> 1.3 <sup>j</sup>
10	4-Me-C <sub>6</sub> H <sub>4</sub>	Ph	CI: trace (homogeneous) <sup>k</sup>

Reaction conditions:  $(NH_4)_2PdCl_4@poly(mPO)$ **1a** (10 mg, 0.04 mol%), Ar-X (1.5 mmol), R-B(OH)<sub>2</sub> (1.8 mmol), TBAB (1.5 mmol), K<sub>3</sub>PO<sub>4</sub> (4.5 mmol), H<sub>2</sub>O (0.6 mmol), 95°C, 20 hr. <sup>[a]</sup> 0 mmol TBAB

<sup>[b]</sup> 10 mg  $(NH_4)_2$ PdCl<sub>4</sub>@poly(*m*PO)**1a**, 400 PPM, <sup>[c]</sup> 1 mg  $(NH_4)_2$ PdCl<sub>4</sub>@poly(*m*PO)**1a**, 40 PPM, <sup>[d]</sup> 0.1 mg  $(NH_4)_2$ PdCl<sub>4</sub>@poly(*m*PO)**1a**, 4 PPM)

 $^{[e]} 0.1 mg (NH_4)_2 PdCl_4 @poly(mPO) 1a, 400 PPB, Ar-X (15 mmol), R-B(OH)_2 (18 mmol), K_3 PO_4 (45 mmol), H_2 O (6 mL), 95°C, 20 hr. Initial reaction rates were determined after 3 h. (NH_4)_2 PdCl_4 @poly(mPO) 1a was reused in five sequential reactions (<sup>[f]</sup> 1<sup>st</sup> run, <sup>[g]</sup> 2<sup>nd</sup> run, <sup>[h]</sup> 3<sup>rd</sup> run, <sup>[i]</sup> 4<sup>th</sup> run, <sup>[j]</sup> 5<sup>th</sup> run)$ 

<sup>[k]</sup> (NH<sub>4</sub>)<sub>2</sub>PdCl<sub>4</sub> (1.2 mg), 4,6-dimethoxypyrimidine (4.7 mg), Ar-X (1.5 mmol), R-B(OH)<sub>2</sub> (1.8 mmol), TBAB (1.5 mmol), K<sub>3</sub>PO<sub>4</sub> (4.5 mmol), H<sub>2</sub>O (0.6 mmol), 95°C, 20 hr.

In order to further showcase the versatility of this catalyst platform, we demonstrated its utility in mediating Heck coupling under aqueous conditions (Scheme 2).

$$\begin{array}{cccc} Ph-X & + & & \\ Ph-X & + & & \\ 1.0 \text{ mmol} & 2.0 \text{ mmol} & 2.0 \text{ mmol} & 95^{\circ}\text{C}, 20 \text{ hr} & \\ \end{array} \begin{array}{c} (NH_4)PdCI_4@Poly(\textit{mPO})\textbf{1a} \ (0.1 \text{ mol}\%) \\ H_2O \ (2.0 \text{ mL}), \\ 95^{\circ}\text{C}, 20 \text{ hr} & \\ 62-95\% \ (GC) \end{array}$$

 $\begin{array}{l} {\sf R} = {\sf CO}_2 {\sf Bu} {:} \; 95\% \; ({\sf X}{=}{\sf I}), \; 62\% \; ({\sf X}{=}{\sf Br}) \\ {\sf R} = {\sf Ph} {:} \; 67\% \; ({\sf X}{=}{\sf I}) \end{array}$ 

#### Scheme 2. Aqueous Heck coupling

 Table 2.
 Comparison of Pd@poly(mPO) vs. commercial catalysts for Suzuki coupling.

	TON	TOF
Pd@poly(mPO)1a <sup>this work</sup>	1,900,000	95,000/hr
Pd/C <sup>ref 17</sup>	333	28/hr
Pd/C <sup>ref 18</sup>	28	28/hr
Pd/C <sup>ref 19</sup>	20,000	16,600/hr
Pd(PPh <sub>3</sub> ) <sub>4</sub> <sup>ref 20</sup>	33	5.5/hr
Pd <sub>2</sub> (dba) <sub>3</sub> /PtBu <sub>3</sub> <sup>ref 21</sup>	61	12/hr
Pd (trace impurities in	61,875,000	50,000,000/hr
$Na_2CO_3)^{ref 22}$		

The modular synthesis of poly(*m*POs) offers a tunable scaffold from which to design reusable catalysts that are effective in the PPM-PPB metal loading range. We introduce a novel 4,7dichloro-1,10-phenanthroline monomer previously unused in the nascent poly(*m*PO) field, or the similar but more developed oxacalixarene field. The active catalysts were prepared by coordinative convolution of these poly(*m*POs) with  $(NH_4)_2PdCl_4$  in CHCl<sub>3</sub>/H<sub>2</sub>O. Reactivity toward styrene hydrogenation could be specifically regulated for aqueous or non-polar environments by modulating the hydrophobicity of the polymer scaffold. The catalysts also demonstrated aqueous reactivity for Suzuki and Heck coupling reactions.

#### **Conflicts of interest**

There are no conflicts to declare

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